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Enrichment of the High-Redshift IGM by Galactic Winds

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Abstract. This paper discusses a semi-numerical method of investigating the enrichment of the intergalactic medium by galactic winds. We find that most galaxies at $z \gtrsim 3$ should be driving winds, and that (if these winds are similar to those at low z) these winds should escape to large distances. Our calculations – which permit exploration of a large region of model parameter space – indicate that the wind velocity, the mass of the wind-driving galaxies, the fraction of ambient material entrained, and the available time (between wind launch and the observed redshift) all affect wind propagation significantly; other physical effects can be important but are sub-dominant. We find that under reasonable assumptions, the enrichment by $3 \lesssim z \lesssim 6$ galaxies could account for the quantity of metals seen in the Ly α forest, though it is presently unclear whether this enrichment is compatible with the intergalactic medium’s detailed metal distribution or relative quiescence.

1. Introduction

Although in the standard hot big-bang cosmology all heavy elements (‘metals’) form in stars, which are in turn expected to form in galaxies, the intergalactic medium (IGM) from which galaxies form is nevertheless enriched with metals,

at all redshifts and densities yet observed. Even in rather low density (overdensity $\delta \lesssim 5$) regions, the IGM appears to be polluted to $\gtrsim 0.1\%$ solar metallicity, as demonstrated by metal lines in Ly α absorption systems (e.g., Cowie et al. 1995). Exactly how this enrichment occurred constitutes one of the most interesting unsolved problems in the study of galaxy and structure formation. Possible enrichment mechanisms which have been discussed in the literature are the dynamical removal of metal-rich gas (in ram-pressure stripping or through galaxy interactions), the ejection of dust by radiation pressure, and supernova-driven galactic winds.

Aguirre et al. (2001a) have recently presented a method of investigating enrichment due to all three mechanisms, using a hybrid numerical/analytical approach in which metals are added to already-completed cosmological hydrodynamic simulations in a way that approximates their distribution by each mechanism. This method has been used to study the pollution of the IGM by dust (Aguirre et al. 2001c) and the enrichment of the low-density IGM at $z \gtrsim 3$ by winds (Aguirre et al. 2001b). Here I focus on the latter topic.

2. Calculating Wind Enrichment

Supernova-driven ‘superwinds’ develop in galaxies when the supernova rate per unit volume is high enough that supernova remnants overlap before they cool. This leads to a single ‘superbubble’ which, if it can break out of the disk, flows into the IGM as a galactic-scale wind. Such outflows are observed nearby in starburst galaxies (e.g., Heckman, Armus, & Miley 1990), and inferred at $z \sim 3$ from the spectra of Lyman-break galaxies (e.g., Pettini et al. 2001). What these observations do *not* tell us is how far into the IGM the winds may propagate (though there are some indications; see below), and to what degree (and with what variation) they enrich the IGM.

To calculate such things using our method we start with a number of outputs from a cosmological simulation incorporating star formation. At each step, we determine which stars have formed since the last step, and assume that they instantaneously generate some yield of metals. These metals are then distributed to neighboring gas particles either ‘locally’, or via a prescription to simulate their dispersal by winds. The accumulated enrichment of the IGM at lower redshifts can then be tracked. In the wind dispersal prescription (see Aguirre et al. 2001a for details), galaxies with a star formation rate per unit area exceeding $\text{SFR}_{\text{crit}} = 0.1 \text{ M}_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ are assumed to drive steady-state, mass-conserving winds with velocity v_{out} at the center of star formation, and with mass outflow rate of 1.3χ times their SFR (with $\chi \sim 1$). The assumed supernova efficiency (χ), critical SFR, and outflow velocity are based on observations of winds in starburst and Lyman-break galaxies. For each of a number N of angles proportional to the galaxy’s mass, a ‘test shell’ is propagated under the forces of gravity, the wind ram pressure, the sweeping up of the ambient medium (assuming a fraction ϵ_{ent} is swept up), and the thermal pressure of the ambient medium. Metals are distributed within the solid angle $4\pi/N$ around the angle in question and within the radius at which the test shell stalls (i.e. has small velocity with respect to the ambient medium).

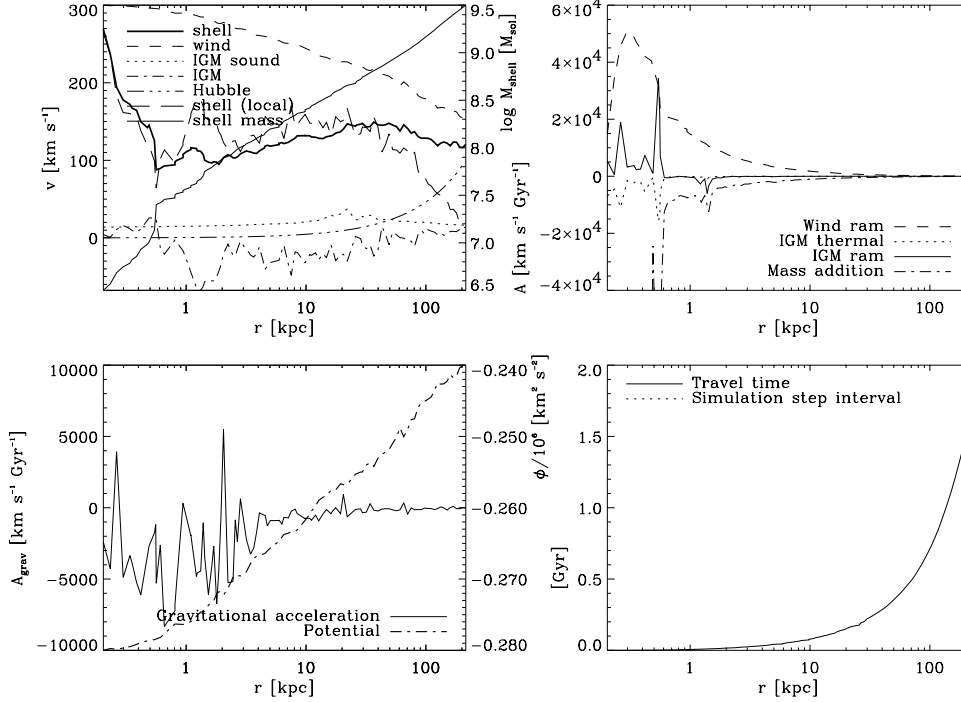


Figure 1. Sample of shell propagation starting at $z = 4$, for a shell with initial velocity of $\sim 300 \text{ km s}^{-1}$ at initial radius 200 pc in a galaxy of baryonic mass $1.2 \times 10^9 M_{\odot}$. **Panel 1:** physical radial velocities (with respect to the galaxy center where appropriate) of the shell, the outflowing wind, the Hubble flow, and the IGM. We give also the local sound speed of the IGM, and the shell velocity in the frame of the ambient gas, as well as the mass of the shell (right axis). **Panel 2:** acceleration $(1/m_{\text{shell}})dp_{\text{shell}}/dt$ of the shell due to the ram pressure of the IGM, the ram pressure of the wind, the thermal pressure of the IGM, and the acceleration due to the addition of mass to the shell (i.e. the term $(v/m)(dm/dt)$ where v and m are the velocity and mass of the shell. Note that this can slow down the shell even if the IGM ram pressure adds momentum). **Panel 3:** Acceleration due to gravity (left axis) and gravitational potential (right axis). **Panel 4:** Elapsed time since launch at initial radius.

To study IGM enrichment by galaxies at $z \gtrsim 3$ we have applied our method to an SPH simulation (see Weinberg et al. 1999) with 128^3 gas and 128^3 dark particles in a 17 Mpc box. This simulation resolves galaxies of baryonic mass $\gtrsim 3 \times 10^8 M_\odot$, and therefore captures the bulk the forming stellar mass at $z \lesssim 6$ (enrichment at higher- z is not captured well). Figure 1 gives an example of the shell propagation in one galaxy at $z \approx 4$, and shows that the ram pressure of the wind, the sweeping up of matter, and the galaxy’s gravity dominate the shell dynamics. In this case, the shell stalls about 200 (physical) kpc from the galaxy center after about 1.5 Gyr. Figure 2 shows how far the shells propagate in a large sample of $z \approx 4$ galaxies assuming $v_{\text{out}} = 300 \text{ km s}^{-1}$ and $\epsilon_{\text{ent}} = 0.1$; we find that these winds do escape to large radii ($\gtrsim 100 \text{ kpc}$) for galaxies of baryonic mass $\lesssim 5 \times 10^9 M_\odot$, limited chiefly by the available time between wind launch and the time corresponding to the redshift at which the enrichment is observed. Our results are in accord with some previous analytical and numerical work, as shown in panel D. There we plot the supernova energy generation rate of the simulated galaxies, and indicate (in the vertically shaded region) the corresponding SFR range found by Pettini et al. (2001). The dashed and dot-dashed lines show the critical wind-escape luminosities of Silich & Tenorio-Tagle (2001) for spherical and disk galaxies, respectively; and the simulated galaxies exceed both. The lower shaded region shows the parameter space probed by Mac Low & Ferrara (1999), who found that winds could escape with large entrainment (‘blow-away’) only from $\sim 10^6 M_\odot$ galaxies – but note that those are the only ones for which their assumed supernova luminosities are comparable to those of the simulated galaxies.

The enrichment of the IGM resulting from the winds is shown in Figure 3 for various assumptions about v_{out} and ϵ_{ent} . The figure reveals that the enrichment of low-density regions is quite sensitive to these parameters, but that for some values the winds are able to enrich most gas particles to metallicities comparable to those observed in the Ly α systems. While the metallicity of simulation gas particles cannot be directly compared to that of absorption-line systems (we are currently implementing a procedure to generate simulated spectra from the simulations), our results indicate that winds at $z \lesssim 6$ can in principle enrich the IGM to the observed level, given reasonable wind parameters.

Another interesting result of our calculations concerns the winds in Lyman-break galaxies observed by Pettini et al. (2001). These winds have $v_{\text{out}} \sim 250 - 1250 \text{ km s}^{-1}$ and mass outflow rates comparable to their SFRs (i.e. $\chi \sim 1$). Using these parameters, we find that even with $\epsilon_{\text{ent}} = 1$ (i.e. the winds snowplough *all* of the gas in their path), winds launched at $z \sim 4$ can escape to $\sim 200 \text{ kpc}$ by $z \sim 3$ (see Figure 4) – there is simply too much momentum contained in these winds for any of the relevant forces to confine them. This prediction may, in fact, be borne out by observations of a significant flux decrement in absorption spectra within $\sim 200 \text{ kpc}$ of Lyman-break galaxies (Pettini, this volume).

3. Conclusions and Questions

We have developed a fast and flexible method of investigating the enrichment of the IGM by various mechanisms, using numerical simulations. Applying this method to winds in simulations at $z \gtrsim 3$, we find a few general results: 1)

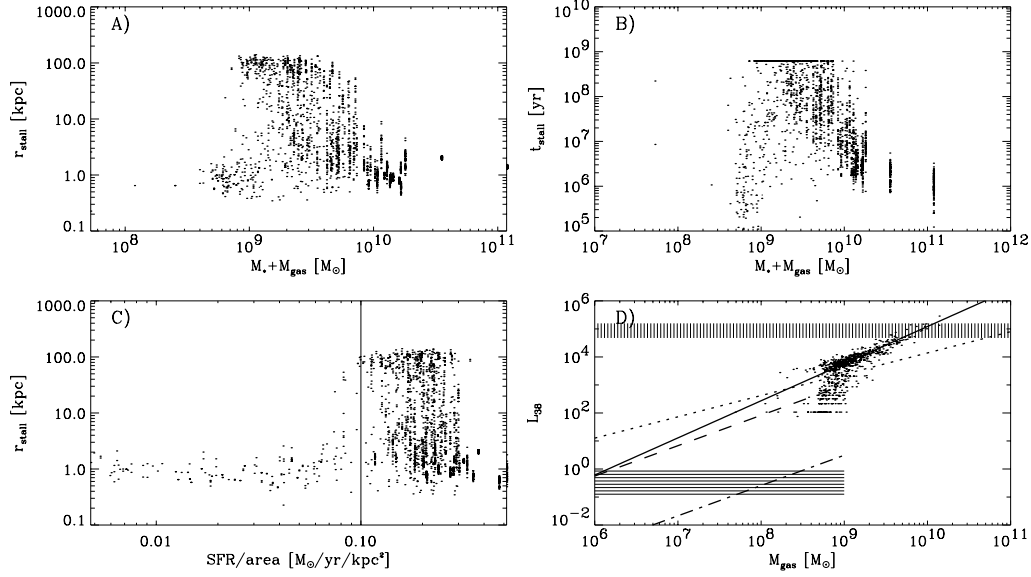


Figure 2. Quantities at wind-driving galaxies launching winds at $z = 4$. **Panel A:** Wind stopping radius r_{stall} (or radius at $z = 3$ if smaller) versus galactic baryonic mass. **B:** Time between shell launch at $z = 4$ and stalling or observation at $z = 3$. **C:** r_{stall} vs. total SFR/area of galaxy. **D:** Supernova energy generation rate in units of $10^{38} \text{ erg s}^{-1}$ versus galactic baryonic mass (see text for more information).

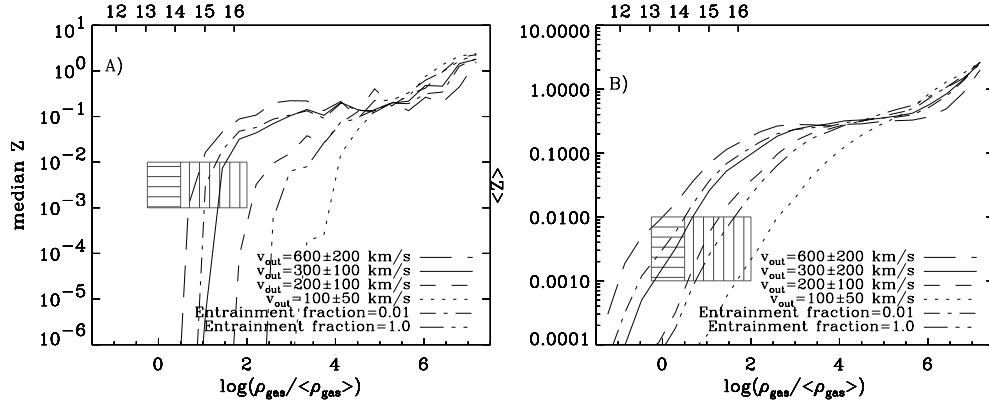


Figure 3. **Panel A:** Median particle metallicity versus $\delta \equiv \rho_{\text{gas}} / \langle \rho_{\text{gas}} \rangle$ for wind models with $v_{\text{out}} = 100, 200, 300, 600 \text{ km s}^{-1}$, and for $v_{\text{out}} = 300 \text{ km s}^{-1}$ with $\epsilon_{\text{ent}} = 0.01$ or $\epsilon_{\text{ent}} = 1$. The top axis (here and in all panels) gives approximate $\log N(\text{H I})$ for an absorber of the given overdensity, using the relation of Schaye (2001). The shaded box roughly indicates the metallicity of low-column density Ly α clouds. **B:** As for panel A, but mass-weighted *mean* metallicities are plotted.

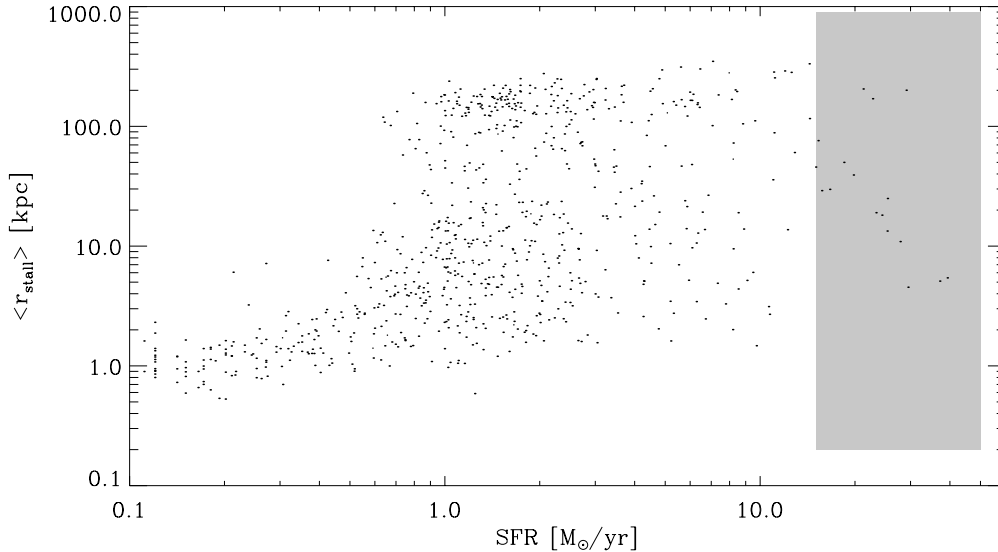


Figure 4. Maximum propagation (until $z = 3$) radius in each galaxy vs. star formation rate, for winds launched at $z = 4$ with $v_{\text{out}} = 750 \pm 500 \text{ km s}^{-1}$ and entrainment fraction unity (wind escape with a more realistic entrainment traction would escape quite easily). The Lyman-break galaxies of Pettini et al. (2001) show SFRs of $10 - 50 \text{ M}_{\odot} \text{ yr}^{-1}$.

Essentially all galaxies at $z \gtrsim 3$ have specific SFRs as high as those of nearby wind-driving galaxies. 2) Winds in low mass ($M \lesssim 10^{10} \text{ M}_{\odot}$) galaxies at $3 \lesssim z \lesssim 6$ with outflow velocities comparable to those in nearby galaxies or as observed in Lyman-break galaxies should escape to large radii. 3) The resulting pollution of the IGM is sufficient to roughly account for the quantity of metals in the observed $\text{Ly}\alpha$ forest. 4) In general, wind propagation is sensitive to the wind outflow velocity and entrainment fraction. Gravity and the assumed outflow velocity determine the mass range of galaxies from which winds can escape, and the distance to which they propagate is limited primarily by the available time.

Our study so far has delineated a number of important theoretical and observational questions. Among them: 1) How uniform is the observed enrichment of the IGM? Are there pristine regions anywhere? 2) How far are metals from galaxies? 3) How important is metal enrichment at $z \gg 6$? Would this metal enrichment be more uniform or less uniform than that at lower redshift? 4) If winds enrich the IGM, do they overly-disturb its properties, spoiling the agreement between simulations and observations of the $\text{Ly}\alpha$ forest? 5) What information about feedback during galaxy formation can be recovered from the observed enrichment of the IGM?

The answers to these questions will shed considerable light on the history of galaxy formation, and on the impact of galaxies on the cosmic medium from which they form.

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